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(54) **VECTOR PROCESSOR HAVING INSTRUCTION SET WITH SLIDING WINDOW NON-LINEAR CONVOLUTIONAL FUNCTION**

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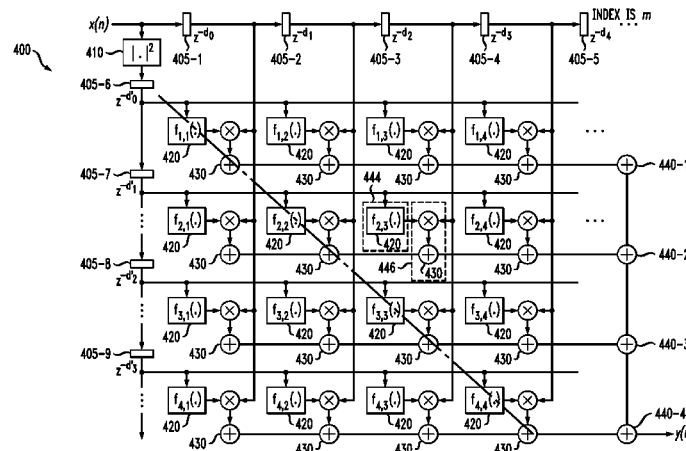
(52) **U.S. Cl.**  
CPC ..... **H04L 5/1461** (2013.01); **G06F 9/30036** (2013.01); **G06F 17/15** (2013.01);  
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(57) **ABSTRACT**

A processor is provided having an instruction set with a sliding window non-linear convolution function. A processor obtains a software instruction that performs a non-linear convolution function for a plurality of input delayed signal samples. In response to the software instruction for the non-linear convolution function, the processor generates a weighted sum of two or more of the input delayed signal samples, wherein the weighted sum comprises a plurality of variable coefficients defined as a sum of one or more non-linear functions of a magnitude of the input delayed signal samples; and repeats the generating step for at least one time-shifted version of the input delayed signal samples to compute a plurality of consecutive outputs. The software instruction for the non-linear convolution function is optionally part of an instruction set of the processor. The non-linear convolution function can model a non-linear system with memory, such as a power amplifier model and/or a digital pre-distortion function.

**21 Claims, 11 Drawing Sheets**



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**H04L 25/03** (2006.01)  
**H04L 27/36** (2006.01)  
**H04J 11/00** (2006.01)  
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CPC ..... **G06F 17/50** (2013.01); **G06F 17/5009** (2013.01); **H04B 1/0475** (2013.01); **H04B 1/525** (2013.01); **H04B 1/62** (2013.01); **H04J 11/004** (2013.01); **H04L 1/0043** (2013.01); **H04L 25/03012** (2013.01); **H04L 25/03343** (2013.01); **H04L 25/08** (2013.01); **H04L 27/367** (2013.01); **H04L 27/368** (2013.01); **H04B 2001/0425** (2013.01)
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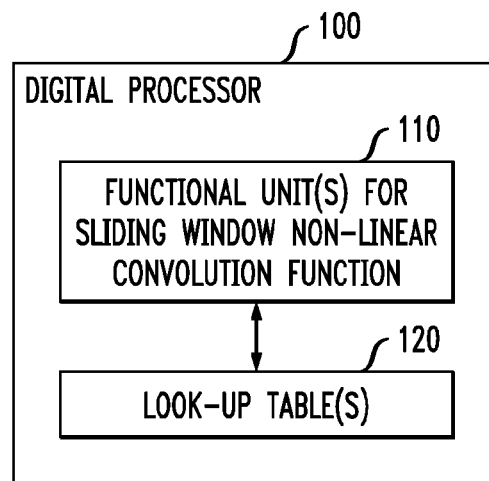
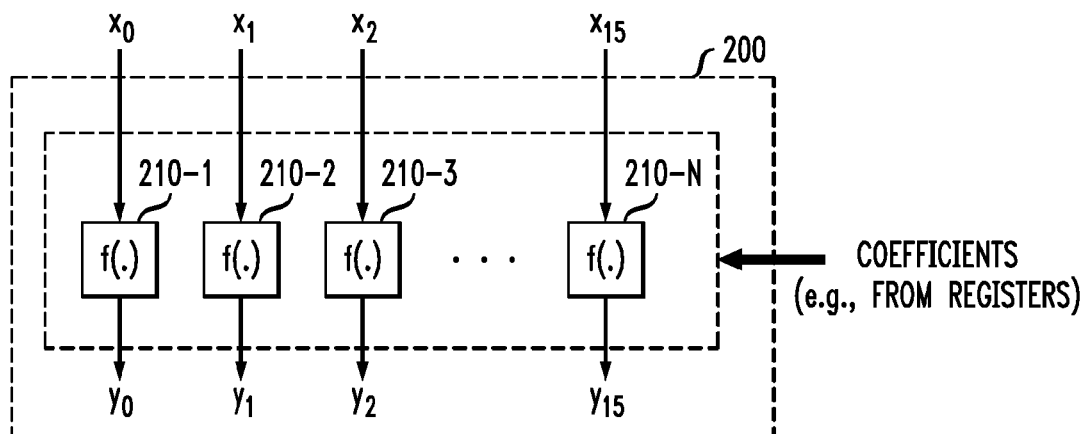
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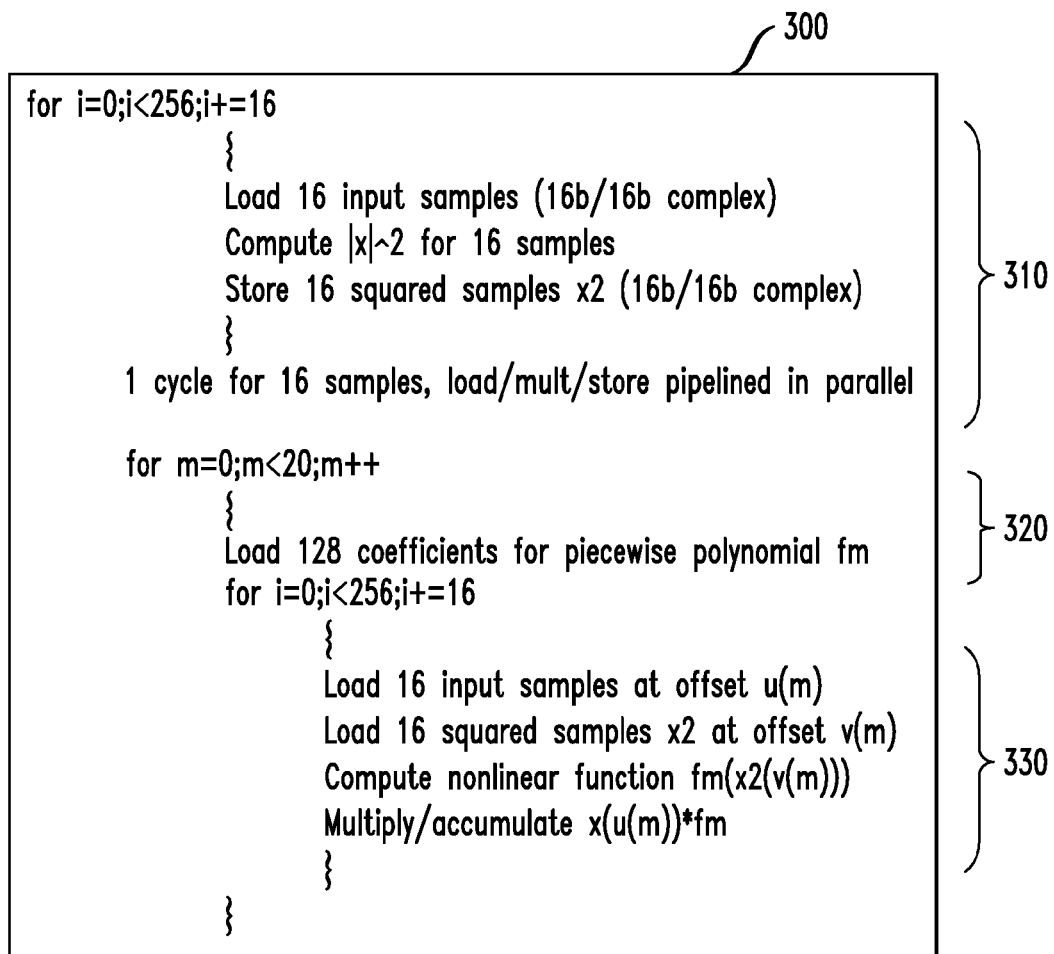
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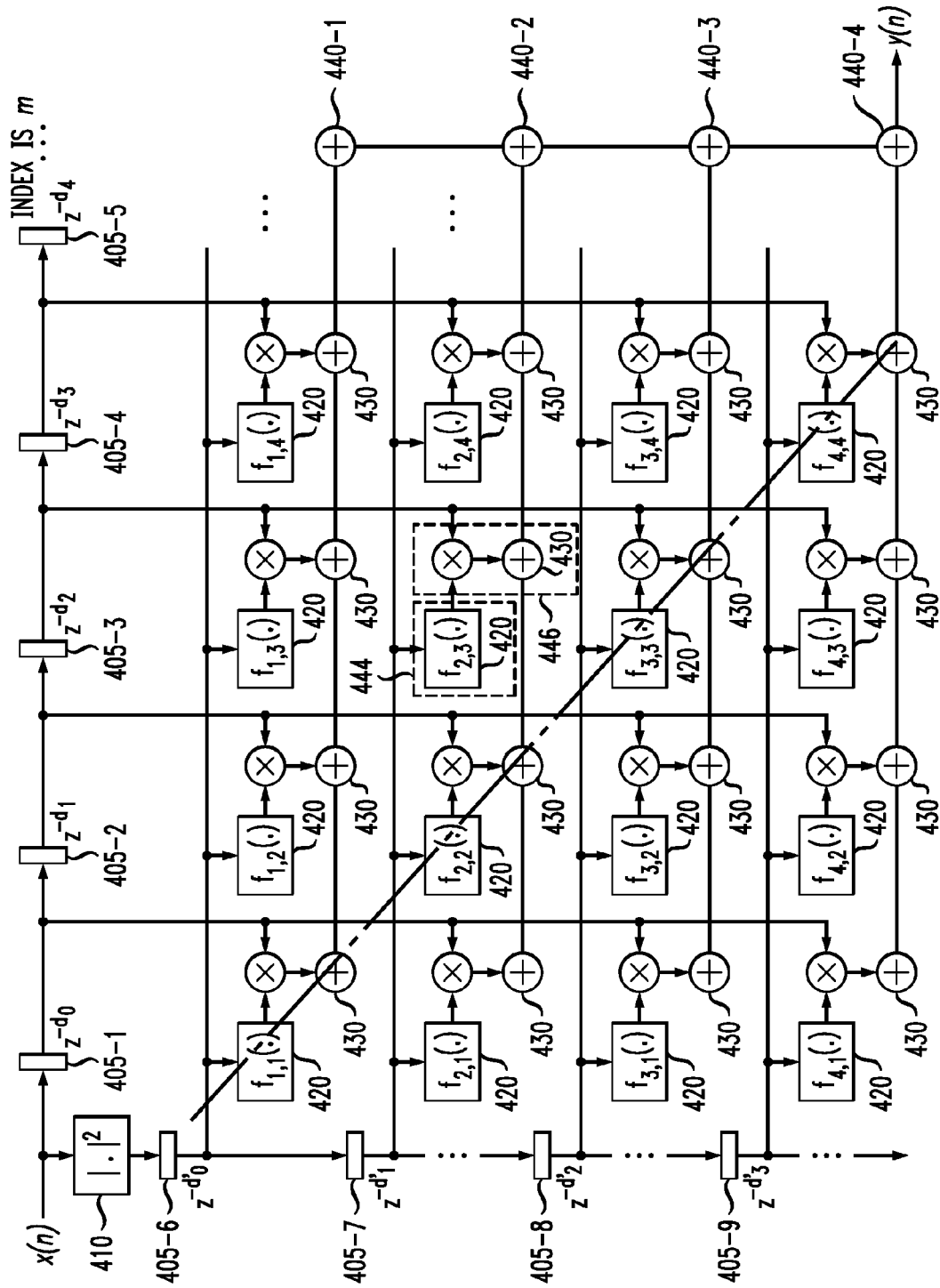
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*FIG. 1**FIG. 2*

*FIG. 3*

**FIG. 4A**



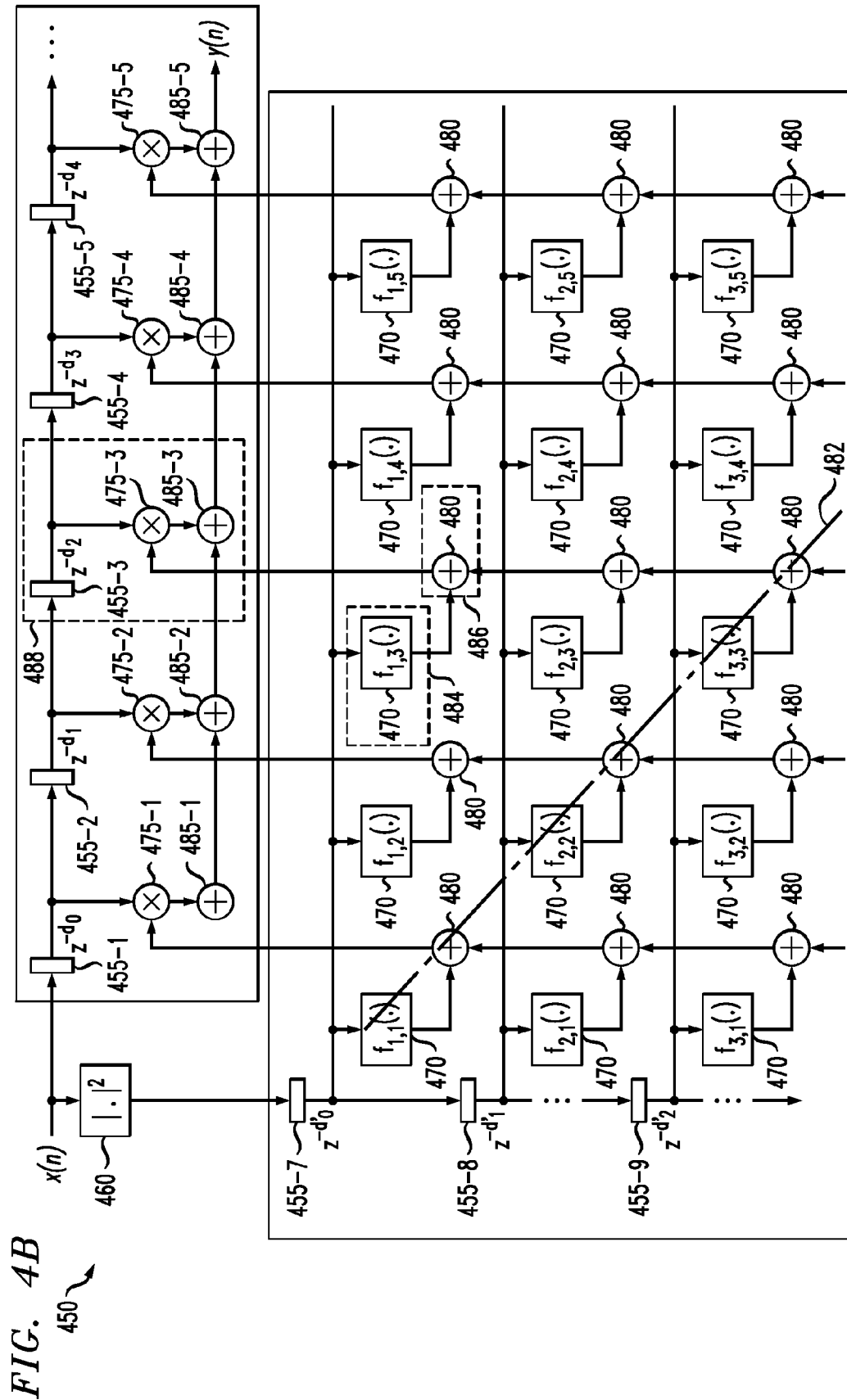
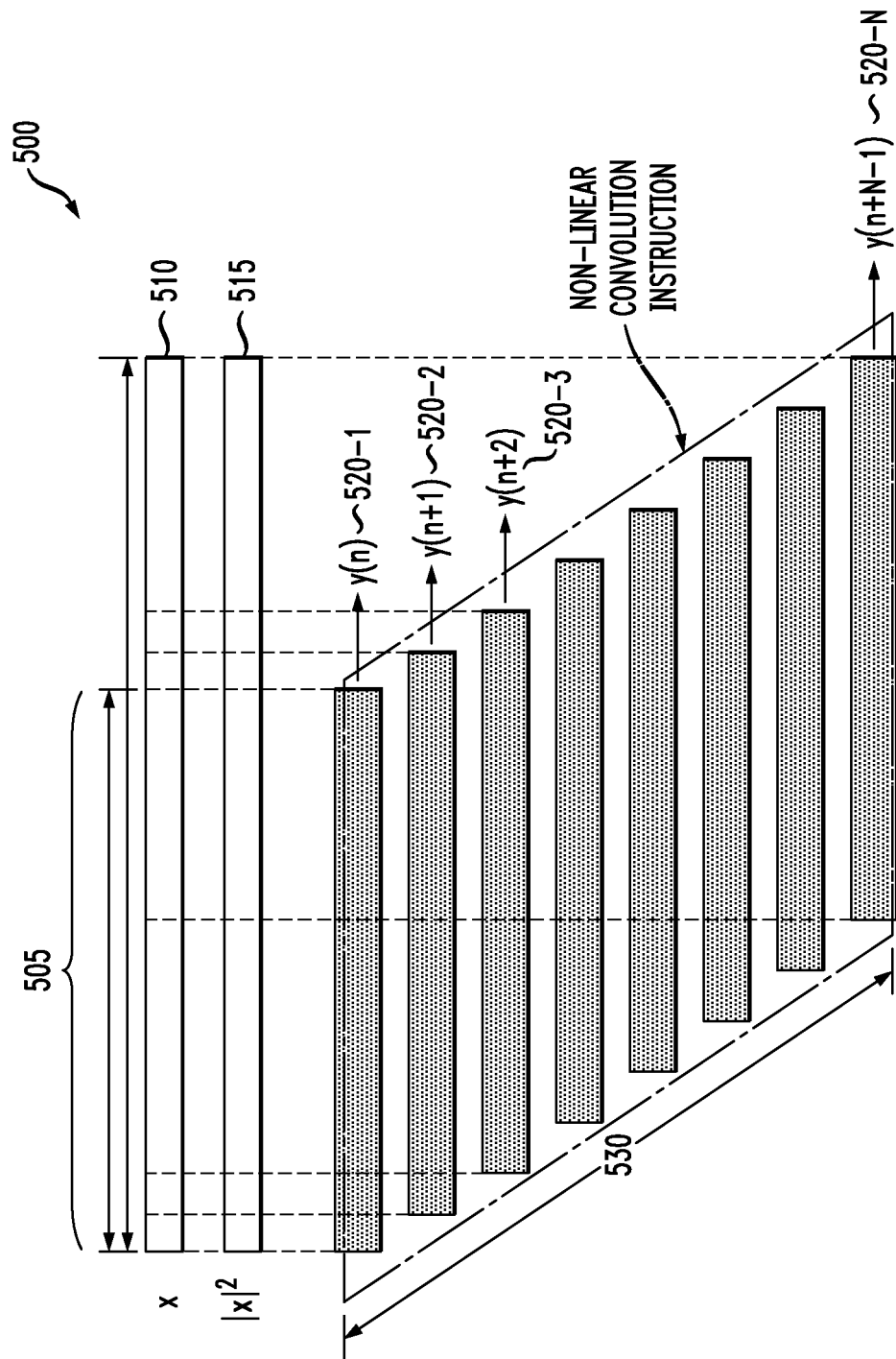


FIG. 5





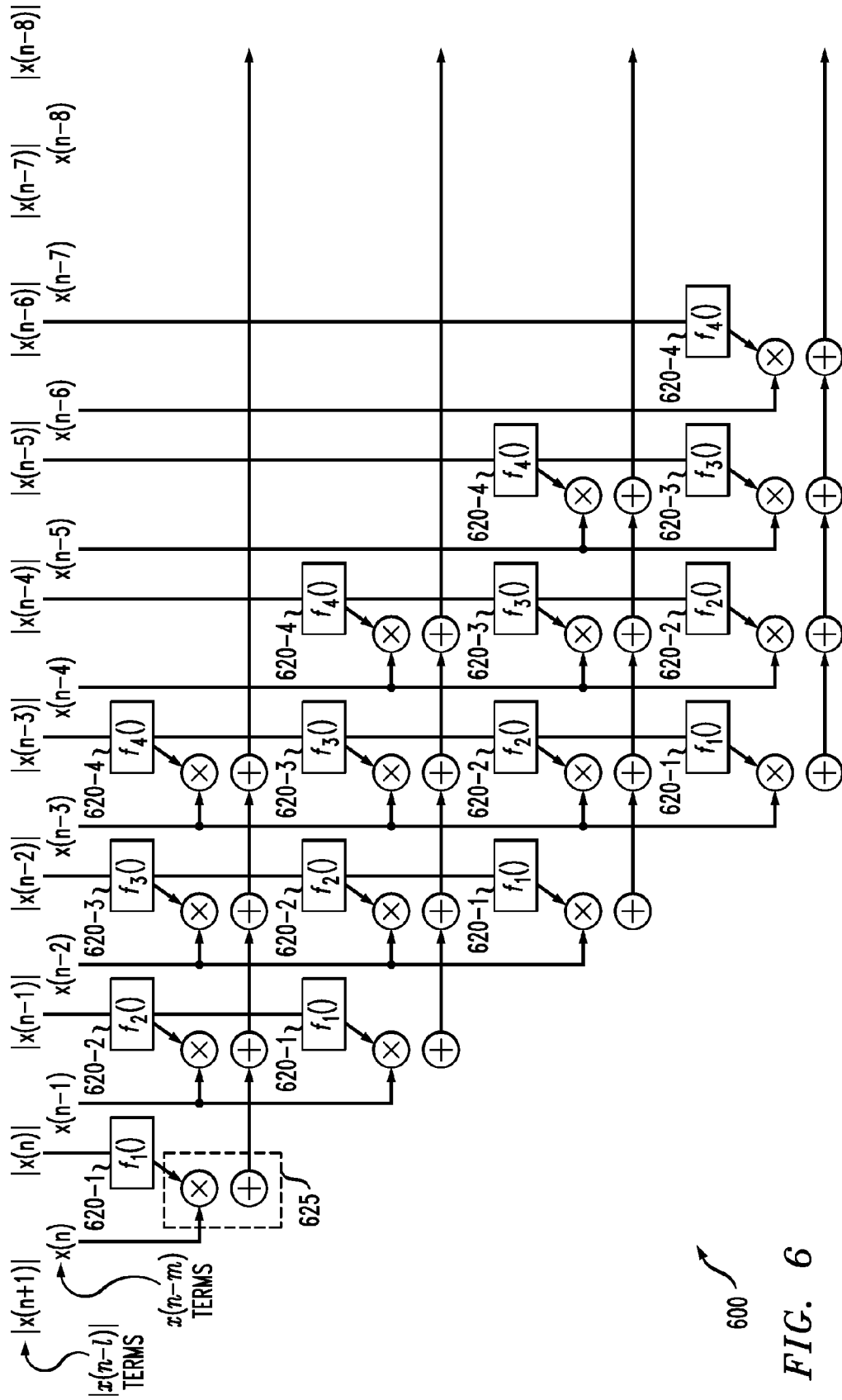


FIG. 6

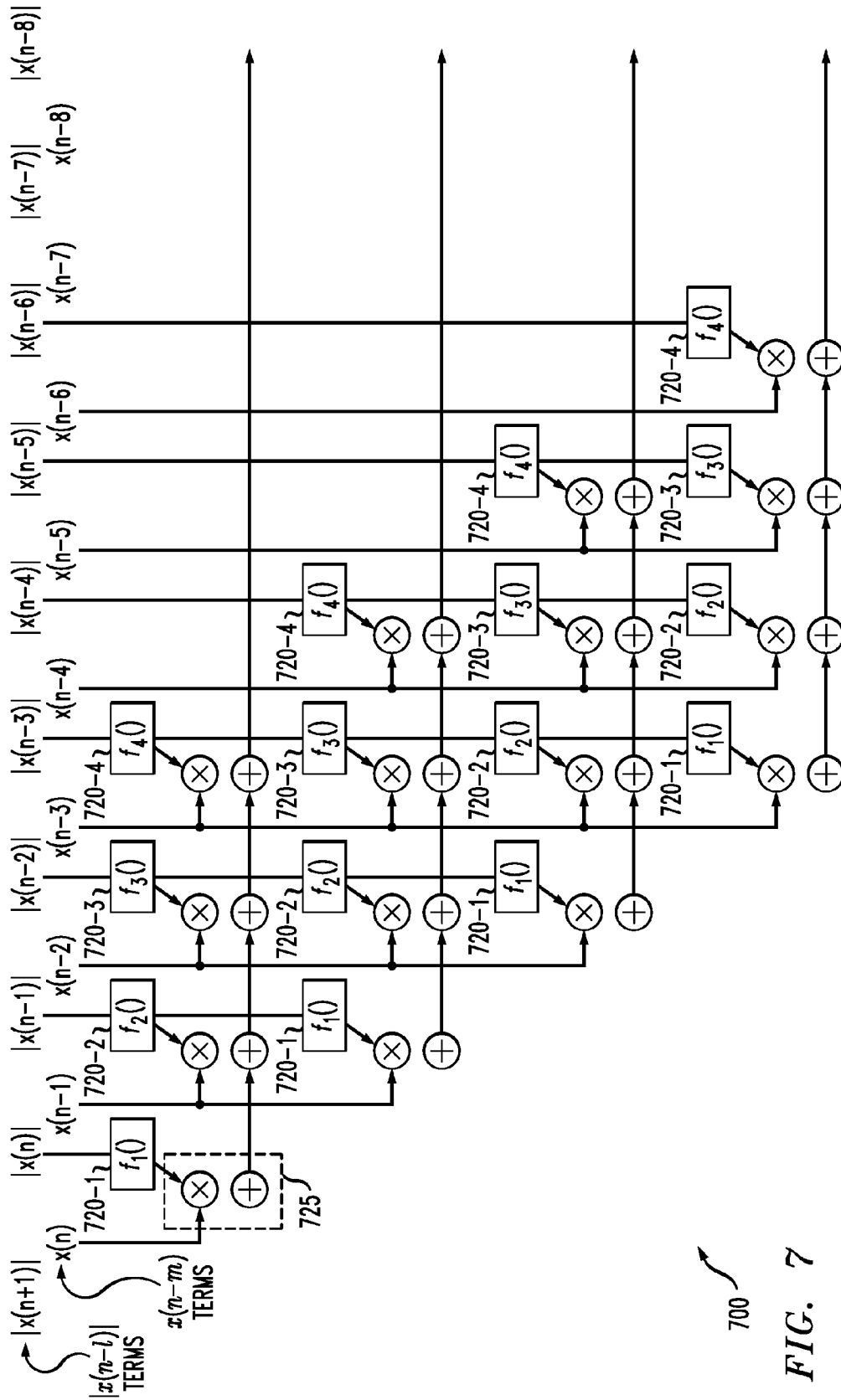


FIG. 7

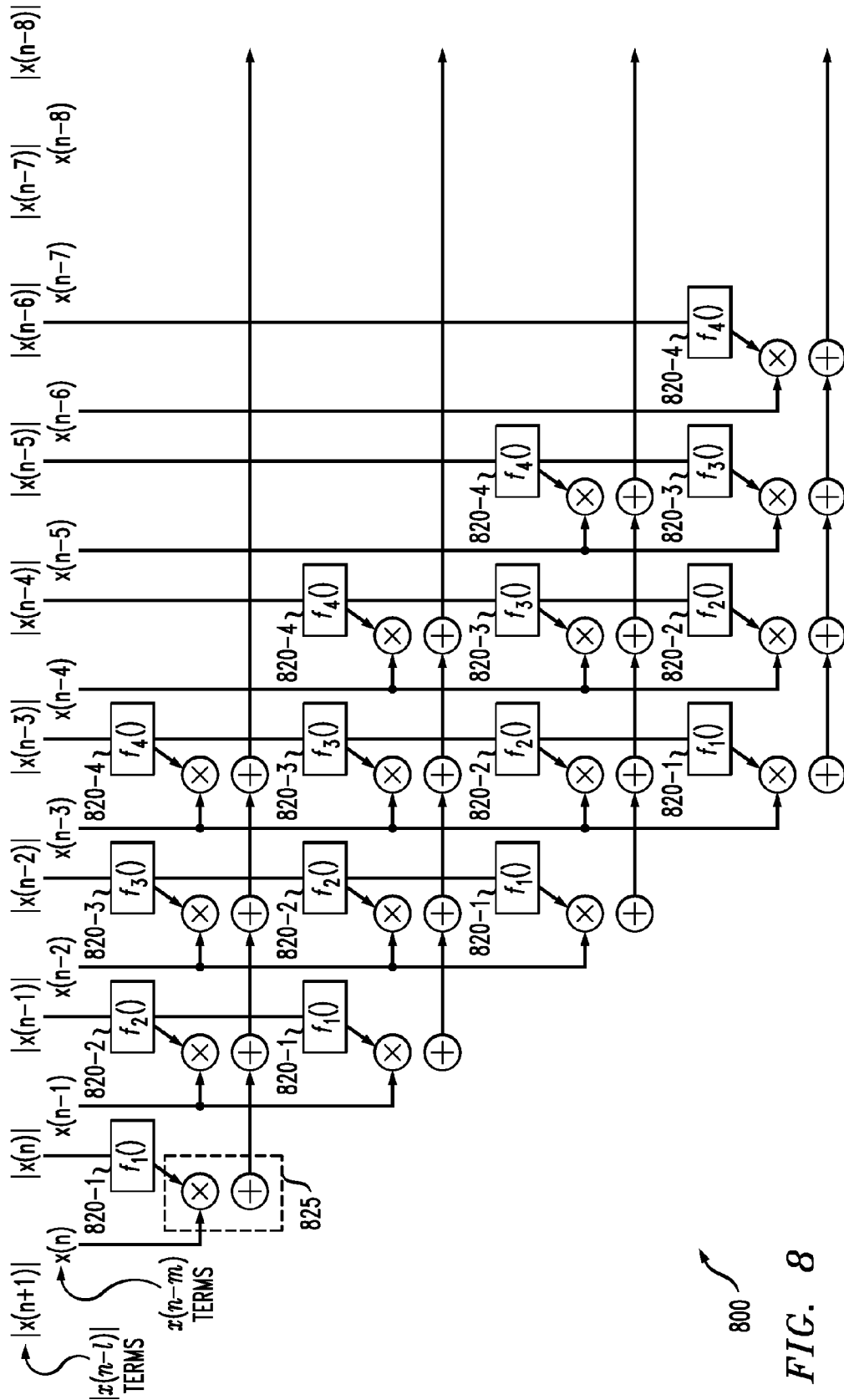
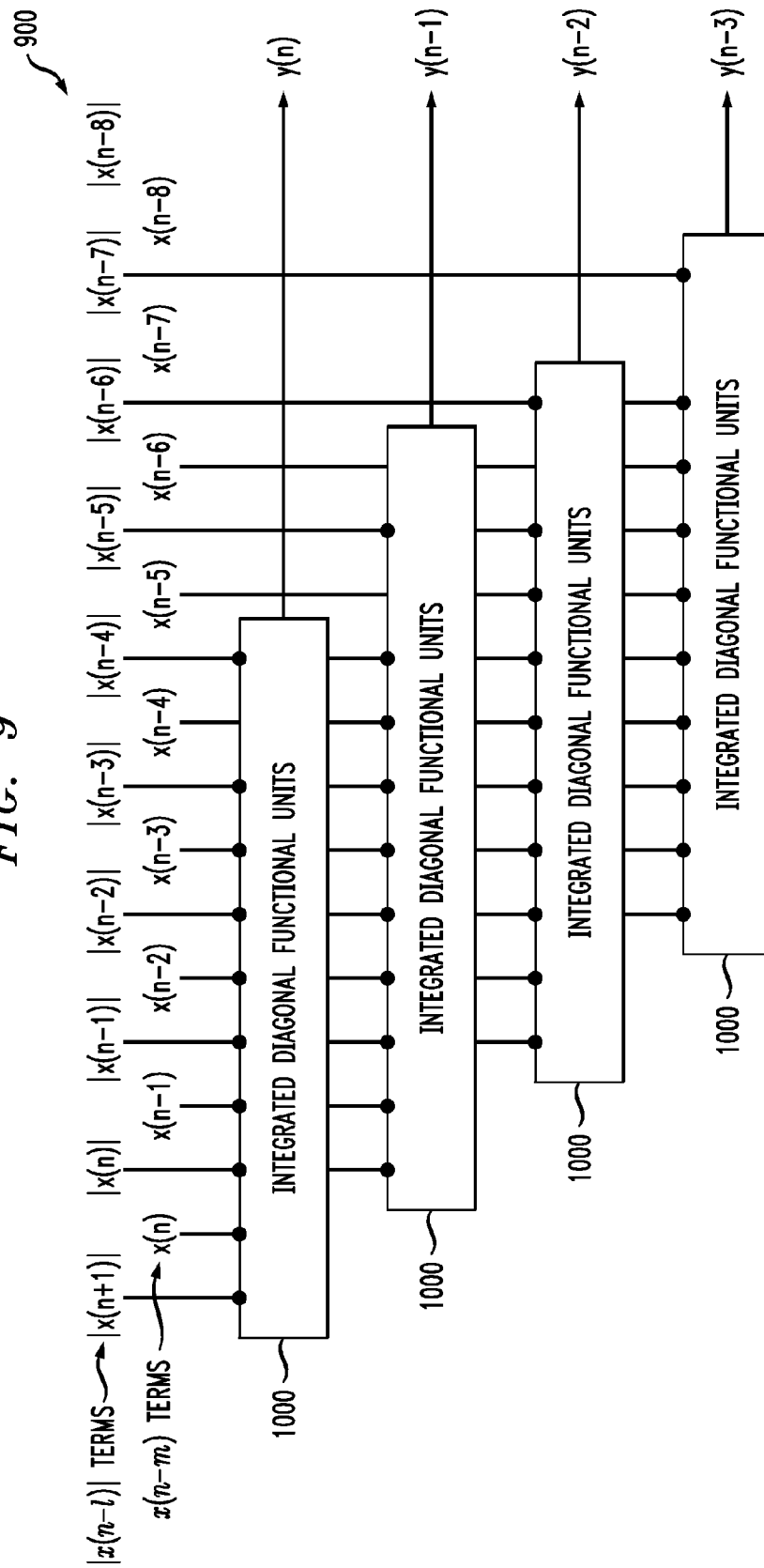


FIG. 9



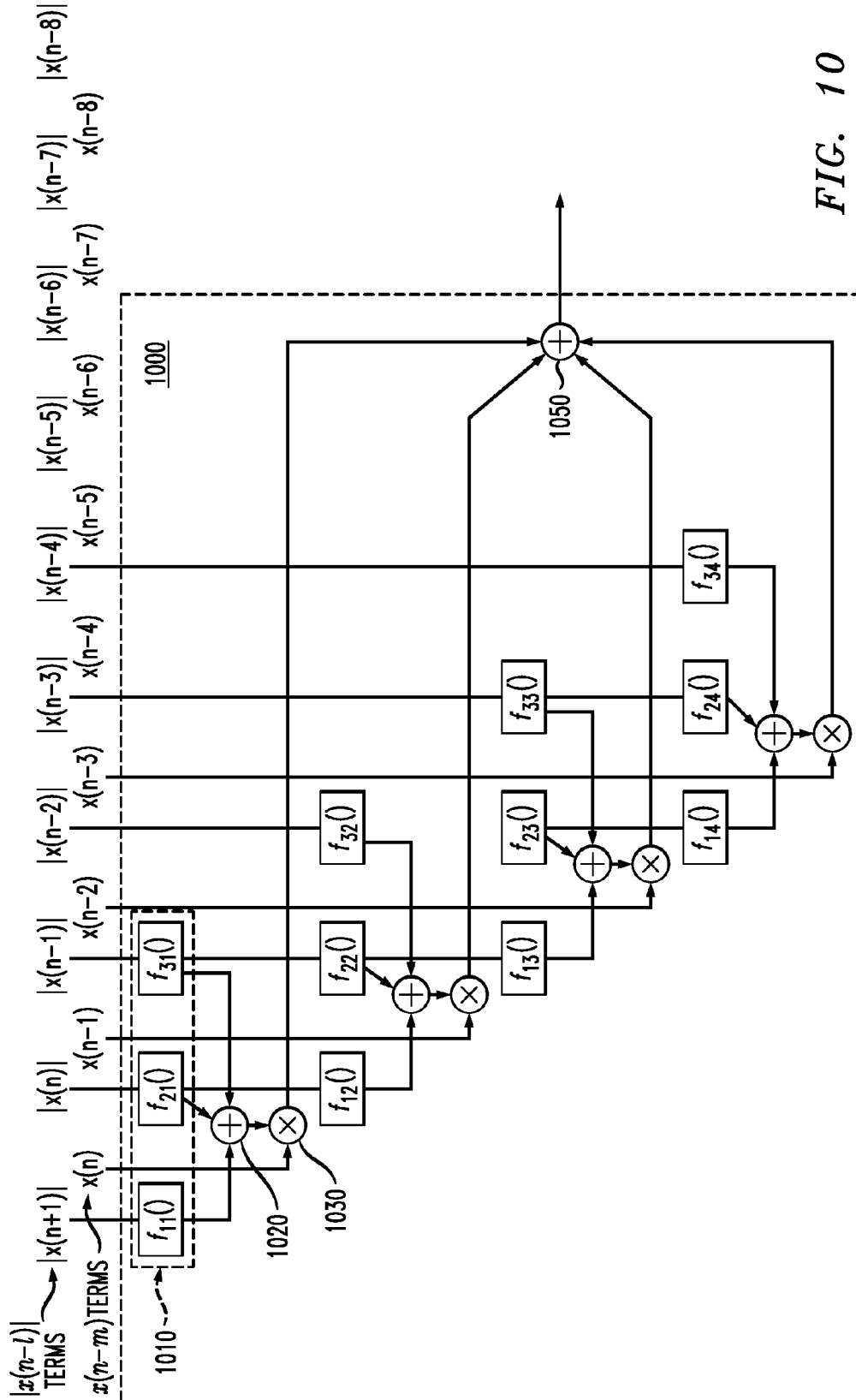
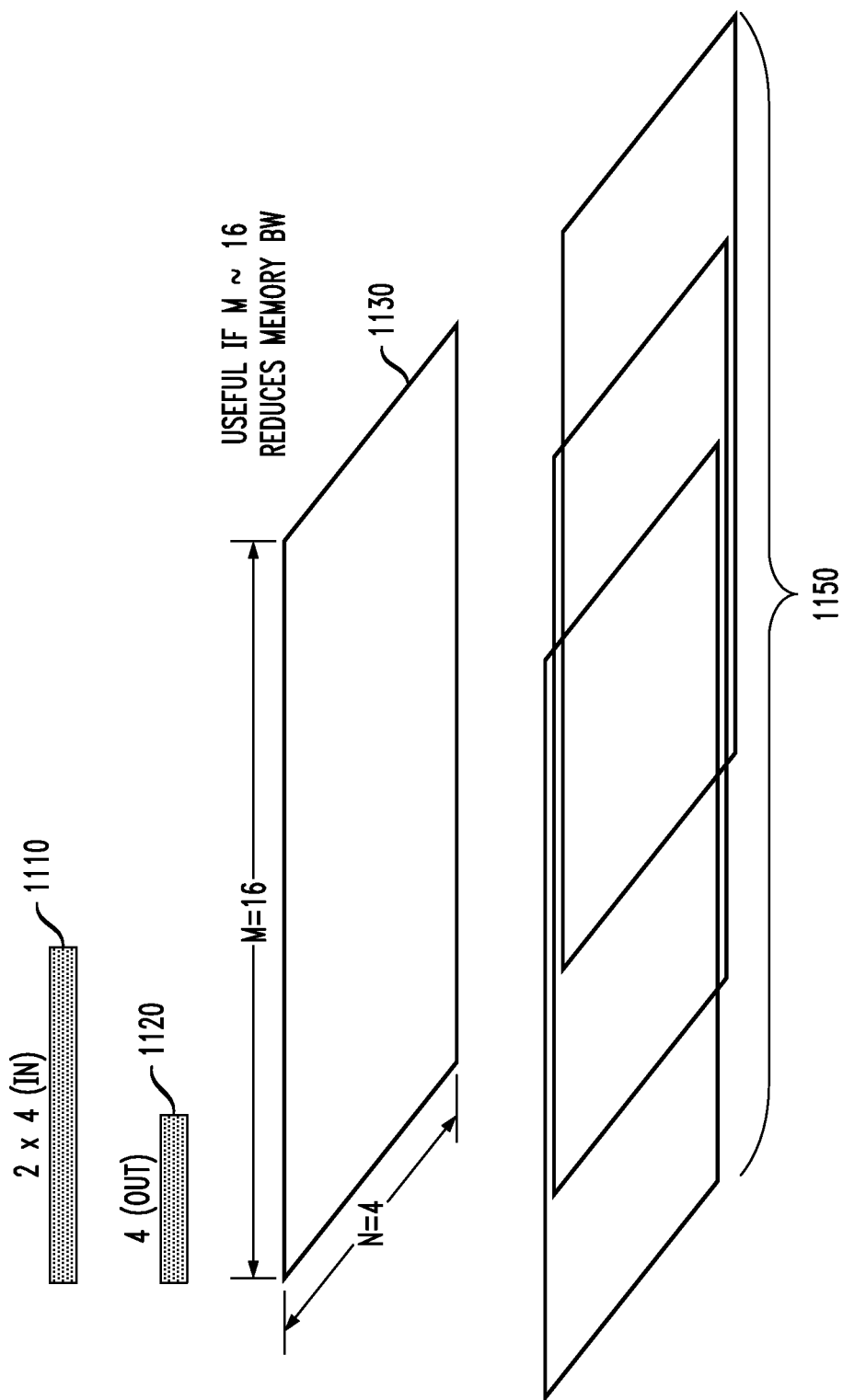


FIG. 10

FIG. 11



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# VECTOR PROCESSOR HAVING INSTRUCTION SET WITH SLIDING WINDOW NON-LINEAR CONVOLUTIONAL FUNCTION

## CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims priority to U.S. Patent Provisional Application Ser. No. 61/812,858, filed Apr. 17, 2013, entitled "Digital Front End (DFE) Signal Processing," incorporated by reference herein.

The present application is related to PCT Patent Application No. PCT/US12/62179, filed Oct. 26, 2012, entitled "Software Digital Front End (SoftDFE) Signal Processing," PCT Patent Application No. PCT/US12/62182, filed Oct. 26, 2012, entitled "Vector Processor Having Instruction Set With Vector Convolution Function For FIR Filtering," PCT Patent Application No. PCT/US12/62186, filed Oct. 26, 2012, entitled "Processor Having Instruction Set with User-Defined Non-Linear Functions for Digital Pre-Distortion (DPD) and Other Non-Linear Applications," and U.S. patent application Ser. No. 12/849,142, filed Aug. 3, 2010, entitled "System and Method for Providing Memory Bandwidth Efficient Correlation Acceleration," each incorporated by reference herein.

## FIELD OF THE INVENTION

The present invention is related to digital signal processing techniques and, more particularly, to techniques for digital processing of non-linear functions.

## BACKGROUND OF THE INVENTION

Digital signal processors (DSPs) are special-purpose processors utilized for digital processing. Digital signal processing algorithms typically require a large number of mathematical operations to be performed quickly and efficiently on a set of data. DSPs thus often incorporate specialized hardware to perform software operations that are often required for math-intensive processing applications, such as addition, multiplication, multiply-accumulate (MAC), and shift-accumulate. Such basic operations can be efficiently carried out utilizing specialized high-speed multipliers and accumulators.

A vector processor implements an instruction set containing instructions that operate on vectors (i.e., one-dimensional arrays of data). The scalar DSPs, on the other hand, have instructions that operate on single data items. Vector processors offer improved performance on certain workloads.

PCT Patent Application No. PCT/US12/62186, filed Oct. 26, 2012, entitled "Processor Having Instruction Set with User-Defined Non-Linear Functions for Digital Pre-Distortion (DPD) and Other Non-Linear Applications," discloses a processor that supports non-linear functions that include one or more parameters specified by a user, such as filter coefficient values or values from a look-up table (LUT). While the disclosed techniques have significantly improved the performance of software implementations of DPD and other non-linear applications, a need remains for digital processors, such as DSPs and vector processors, having an instruction set that supports a sliding window non-linear convolution function.

## SUMMARY OF THE INVENTION

Generally, a processor is provided having an instruction set with a sliding window non-linear convolution function.

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According to one aspect of the invention, a processor obtains at least one software instruction that performs at least one non-linear convolution function for a plurality of input delayed signal samples. In response to the at least one software instruction for the at least one non-linear convolution function, the processor performs the following steps: generating a weighted sum of two or more of the input delayed signal samples, wherein the weighted sum comprises a plurality of variable coefficients defined as a sum of one or more non-linear functions of a magnitude of the input delayed signal samples; and repeating the generating step for at least one time-shifted version of the input delayed signal samples to compute a plurality of consecutive outputs, wherein the at least one software instruction for the at least one non-linear convolution function is part of an instruction set of the processor.

The variable coefficients defined by a non-linear function of a magnitude of the input delayed signal samples are optionally implemented using one or more look-up tables. The non-linear convolution function can model a non-linear system with memory, such as a power amplifier model and/or a digital pre-distortion function. The non-linear convolution function is optionally implemented using one or more look-up tables having linear and/or polynomial interpolation.

A more complete understanding of the present invention, as well as further features and advantages of the present invention, will be obtained by reference to the following detailed description and drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic block diagram of an exemplary digital processor that incorporates features of the present invention;

FIG. 2 is a schematic block diagram of an exemplary vector-based digital processor that processes one or more numbers simultaneously in accordance with an embodiment of the present invention;

FIG. 3 illustrates exemplary pseudo code to implement a DPD function in software on a vector processor of 16 component vectors using a user-defined non-linear instruction  $f_{m,d}$ ;

FIGS. 4A and 4B are graphical illustrations of exemplary functional block diagrams;

FIG. 5 illustrates a sliding window non-linear convolution function that incorporates features of the present invention;

FIGS. 6 through 8 are graphical illustrations of exemplary functional block diagrams that compute diagonal terms, lower diagonal terms and upper diagonal terms, respectively;

FIG. 9 is a graphical illustration of an exemplary functional block diagram that computes the diagonal, upper diagonal and lower diagonal terms in a single instruction call;

FIG. 10 is a graphical illustration of an exemplary integrated diagonal functional unit of FIG. 9 in further detail; and

FIG. 11 illustrates an alternate asymmetric embodiment of the invention, where an exemplary input is processed by an asymmetric array of functional units using a plurality of overlapping windows and the output comprises a vector.

## DETAILED DESCRIPTION

Aspects of the present invention provide digital processors, such as DSPs and vector processors, having an instruction set that supports a sliding window non-linear convolution function. As used herein, the term "digital processor" shall be a processor that executes instructions in program code, such as a DSP or a vector processor. It is further noted that the disclosed complex exponential function can be applied for val-

ues of  $x$  that are scalar or vector inputs. The present invention can be applied, for example, in handsets, base stations and other network elements.

FIG. 1 is a schematic block diagram of an exemplary digital processor **100** that incorporates features of the present invention. The exemplary digital processor **100** can be implemented as a DSP or a vector processor. As shown in FIG. 1, the exemplary digital processor **100** includes one or more functional units **110** for a sliding window non-linear convolution function. In addition, the digital processor **100** comprises one or more look-up tables **120** that store, for example, discrete points that define the non-linear function.

Generally, if the digital processor **100** is processing software code that includes a predefined instruction keyword corresponding to a sliding window non-linear convolution function and any appropriate operands for the function, the instruction decoder must trigger the appropriate functional units **110** that are required to process the instruction. It is noted that a functional unit **110** can be shared by more than one instruction.

Generally, aspects of the present invention extend conventional digital processors to provide an enhanced instruction set that supports sliding window non-linear convolution functions. The digital processor **100** in accordance with aspects of the present invention receives at least one software instruction that performs a non-linear convolution function for a plurality of input delayed signal samples. In response to the software instruction for the non-linear convolution function, the digital processor **100** generates a weighted sum of two or more of the input delayed signal samples. The weighted sum comprises a plurality of variable coefficients defined as a sum of one or more non-linear functions of a magnitude of the input delayed signal samples. The weighted sum is calculated for at least one time-shifted version of the input delayed signal samples to compute a plurality of consecutive outputs.

The non-linear convolution function can be expressed as follows:

$$y(n+k) = \sum_{l=0}^{L-1} \sum_{m=0}^{M-1} f_{l,m}(|x(n+k-l)|)x(n+k-m), \quad (1)$$

$0 \leq k \leq N-1$ .

The variables in equation (1) are defined further below in conjunction with FIG. 5. A special case of the non-linear convolution function can be expressed as follows:

$$y(n+k) = \sum_{l=0}^{M-1} \sum_{m=0}^{M-1} f_{l,m}(|x(n+k-l)|)x(n+k-m), \quad (2)$$

$0 \leq k \leq N-1$ .

Thus, the non-linear convolution function computes multiple non-linear outputs, recognizing data re-use due to a sliding window type of operation. In the above sums,  $L \times M$  LUTs need to be processed. In practice, if the  $L \times M$  number exceeds the capability of the processor instruction, only a subset (e.g., 8) are processed for each cycle. To produce the complete sum, additional passes are performed on the input samples block and accumulated over previous results to produce the final values of the output signal,  $y$ .

The disclosed sliding window non-linear convolution functions may be employed, for example, for digital pre-distortion (DPD) and other non-linear signal processing.

As indicated above, PCT Patent Application No. PCT/US12/62186, filed Oct. 26, 2012, entitled "Processor Having Instruction Set with User-Defined Non-Linear Functions for Digital Pre-Distortion (DPD) and Other Non-Linear Applications," discloses a processor that supports non-linear functions that include one or more parameters specified by a user, such as filter coefficient values or values from a look-up table. Each execution of the user-specified non-linear function produces a single output.

In addition, PCT Patent Application No. PCT/US12/62182, filed Oct. 26, 2012, entitled "Vector Processor Having Instruction Set With Vector Convolution Function For FIR Filtering" discloses a vector processor having an instruction set with a vector convolution function. Among other benefits, the disclosed vector processor computes multiple outputs in a single cycle. Generally, a disclosed vector convolution function computes the convolution of  $N$ -bit complex data ( $N/2$ -bit real and  $N/2$ -bit imaginary) and complex antipodal data (e.g., coefficients). The exemplary vector convolution function receives an input vector of  $N_1 + N_2 - 1$  input samples and processes time shifted versions of  $N_1$  samples of the input vector  $N_1$  and fixed coefficients, and for each time shifted-version (each time lag) produces an FIR output value. An output vector is comprised of the  $N_2$  output values.

Aspects of the present invention recognize that the time shifted versions of input samples can be stored in a register and re-used multiple times in a single cycle, rather than reloading the input values from memory multiple times. According to one aspect of the invention, multiple consecutive outputs are computed using the time shifted input samples. According to another aspect of the invention, the coefficients are non-linear functions of the input magnitude and can be implemented, for example, using look-up tables.

FIG. 2 is a schematic block diagram of an exemplary vector-based digital processor **200** that processes one or more numbers simultaneously in accordance with an embodiment of the present invention. Generally, the vector-based implementation of FIG. 2 increases performance by reducing a number of operations per second, relative to a scalar implementation, by performing more operations concurrently using less instructions (e.g., MAC and other non-linear functions). Thus, the vector-based digital processor **200** contains plural functional units **210-1** through **210-N** for user-defined non-linear functions  $f(\cdot)$ . For example, a dual digital processor **200** contains two functional units **210-1** and **210-2** that are capable of performing two independent user-defined non-linear function operations concurrently.

Generally, the vector-based digital processor **200** processes a vector of inputs  $x$  and generates a vector of outputs,  $y$ . The exemplary vector-based digital processor **200** is shown for a 16-way vector processor instruction. In one exemplary implementation having 32 segments, for coefficients represented using four cubic polynomial approximation coefficients, in the look-up table there are 128 complex entries (16 bit complex and 16 bit real). In a further variation having 128 segments, and one coefficient per segment, there are 128 complex coefficients for linear interpolation (16 bit complex and 16 bit real).

The exemplary vector-based digital processor **200** thus performs 16 such non-linear operations according to the following equation, and linearly combines them in a single cycle at each call of the vector non-linear instruction computing as an example the non-linear polynomial function:



$$f(x) = \sum_{k=0}^{19} a_k x^k$$

It is noted that in the more general case, different functions may be applied to each component of the vector data of the vector processor.

As shown in FIG. 2, the functional units **210** receive a user-specification, such as the look-up tables or coefficients, from memory for storage in a register.

Non-Linear Filter Implementation of Digital Pre-Distorter

A digital pre-distorter can be implemented as a non-linear filter using a Volterra series model of non-linear systems. The Volterra series is a model for non-linear behavior in a similar manner to a Taylor series. The Volterra series differs from the Taylor series in its ability to capture “memory” effects. The Taylor series can be used to approximate the response of a non-linear system to a given input if the output of this system depends strictly on the input at that particular time. In the Volterra series, the output of the non-linear system depends on the input to the system at other times. Thus, the Volterra series allows the “memory” effect of devices to be captured.

Generally, a causal system with memory can be expressed as:

$$y(t) = \int_{-\infty}^{\infty} h(\tau) x(t-\tau) d\tau$$

In addition, a weakly non-linear system without memory can be modeled using a polynomial expression:

$$y(t) = \sum_{k=1}^{\infty} a_k [x(t)]^k$$

The Volterra series can be considered as a combination of the two:

$$y(t) = \sum_{k=1}^K y_k(t)$$

$$y(t) = \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} h(\tau_1, \dots, \tau_k) x(t-\tau) d\tau$$

In the discrete domain, the Volterra Series can be expressed as follows:

$$y(n) = \sum_{k=1}^K y_k(n)$$

$$y(n) = \sum_{m_1=0}^{M-1} \dots \sum_{m_k=0}^{M-1} h_k(m_1, \dots, m_k) \prod_{l=1}^k x(n-m_l)$$

The complexity of a Volterra series can grow exponentially making its use impractical in many common applications, such as DPD. Thus, a number of simplified models for non-linear systems have been proposed. For example, a memory polynomial is a commonly used model:

$$\begin{aligned} y_{MP}(n) &= \sum_{k=1}^K \sum_{m=0}^{M-1} h_k(m, \dots, m) x^k(n-m) \\ &= \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} h_{k,m,l} |x(n-l)|^k x(n-m) \end{aligned}$$

Another simplified model referred to as a Generalized Memory Polynomial Model, can be expressed as follows (where M indicates the memory depth and K indicates the polynomial order):

$$y(n) = \sum_{m=0}^{M-1} \sum_{l=0}^{M-1} \sum_{k=0}^{K-1} h_{k,m,l} |x(n-l)|^k x(n-m)$$

-continued

$$y(n) = \sum_{m=0}^{M-1} \sum_{l=0}^{M-1} x(n-m) \sum_{k=0}^{K-1} h_{k,m,l} |x(n-l)|^k$$

An equivalent expression of the Generalized Memory Polynomial with cross-products, can be expressed as follows:

$$y(n) = \sum_{m=0}^{M-1} \sum_{l=0}^{M-1} x(n-m) \cdot f_{m,l}(|x(n-l)|) \quad (3)$$

where:

$$f_{m,l}(|x(n-l)|) = \sum_{k=0}^{K-1} h_{k,m,l} |x(n-l)|^k \quad (4)$$

where  $f(x)$  is a non-linear function having one or more user-specified parameters assumed to be accelerated in accordance with an aspect of the invention using the user-defined non-linear instruction `vec_nl`, discussed below. It is noted that other basis functions other than  $x^k$  for non-linear decomposition are possible.

As discussed hereinafter, the user-defined non-linear instruction  $f_{m,l}$  can be processed, for example, by a vector processor, such as the vector processor of FIG. 2. The  $f_{m,l}$  is an  $m \times l$  array of non-linear functions. Each non-linear function can have a user-specified parameter, such a look-up table or coefficients. The look-up table can be a polynomial approximation of the user-defined non-linear instruction  $f_{m,l}$ . In one exemplary embodiment, the look-up table for each user-defined non-linear instruction  $f_{m,l}$  in the  $m \times l$  array can be stored in memory and loaded into a register when the instruction is processed by the vector processor **200** (or even directly loaded from memory into the non-linear convolution functional unit). The input samples can then be evaluated on the individual non-linear instruction  $f_{m,l}$  in the  $m \times l$  array.

FIG. 3 illustrates exemplary pseudo code **300** to implement a DPD function in software on a vector processor of 16 component vectors using a user-defined non-linear instruction  $f_{m,l}$  of equation (3). The exemplary pseudo code **300** comprises a first portion **310** to compute a magnitude of the input  $x$ . In line **320**, the look-up table for an individual non-linear instruction  $f_{m,l}$  in the  $m \times l$  array can be loaded into a register. Thereafter, the exemplary pseudo code **300** comprises a portion **330** to implement equation (3) (e.g., input samples, perform a square operation on the samples, compute the non-linear function and then multiply accumulate the result).

FIG. 4A is a graphical illustration of an exemplary functional block diagram **400** that implements equation (3). In the exemplary embodiments described herein,  $|x|^{2k}$  is used instead of  $|x|^k$ . As shown in FIG. 4A, the exemplary circuit **400** comprises a plurality of delay elements, such as delay elements **405-1** through **405-5** to generate the  $x(n-m)$  term of equation (3) and delay elements **405-6** through **405-9** to generate the  $|x(n-l)|^2$  term of equation (4) by delaying the output of a squaring operation **410**. In addition, the exemplary functional block diagram **400** comprises an array of functional units **420-1,1** through **420-4,4** that receive the appropriate  $|x(n-l)|^2$  term and implement equation (4). The exemplary functional block diagram **400** also comprises a plurality of multipliers ( $\times$ ) that receive the appropriate  $x(n-m)$  term and multiply it with the output of the corresponding  $m,l$  functional unit **420**. The outputs of the multiplication in each row are

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added by adders (+) 430 and the outputs of each adder 430 in a given row are summed by a corresponding adder 440 to generate the output  $y(n)$ .

FIG. 4A also illustrates a diagonal line 442 that is discussed further below in conjunction with FIGS. 6-8.

FIG. 4B provides a graphical illustration 450 of an alternate exemplary functional block diagram 450 that implements equation (3) with a reduced number of multiply operations. As shown in FIG. 4B, the exemplary circuit 450 comprises a plurality of delay elements, such as delay elements 455-1 through 455-5 to generate the  $x(n-m)$  term of equation (3) and delay elements 455-7 through 455-9 to generate the  $|x(n-l)|^2$  term of equation (4) by delaying the output of a squaring operation 460. In addition, the exemplary functional block diagram 450 comprises an array of functional units 470-1,1 through 470-4,4 that receive the appropriate  $|x(n-l)|^2$  term and implements equation (4). Adders 480 compute the non-linear gains (sum of non-linear functions of magnitude of the input).

The exemplary functional block diagram 450 also comprises a plurality of multipliers (x) 475 that receive the appropriate  $x(n-m)$  term and multiply it with the output of the summed output of a column of corresponding  $m,l$  functional units 470. In this manner, the non-linear gains from adders 480 are applied to the input data (complex multiply-accumulate (CMAC) operations). The outputs of the multiplication added by adders (+) 485 to generate the output  $y(n)$ .

FIG. 4B also illustrates a diagonal line 482 that is discussed further below in conjunction with FIGS. 6-8.

#### Sliding Window Non-Linear Convolution Functions

As indicated above, aspects of the present invention recognize that the time shifted versions of input samples can be stored in a register and re-used multiple times in a single cycle, rather than reloading the input values from memory multiple times. Similarly, a given functional unit 470 of the exemplary functional block diagram 450 of FIG. 4B, such as the exemplary functional unit highlighted using a dashed box 484, and the associated exemplary delay, multiplier and adder circuitry highlighted using dashed boxes 486 and 488, are applied to 16 consecutive samples in a single cycle in the exemplary embodiment.

As discussed hereinafter, aspects of the present invention recognize that performance can be further improved relative to the implementations of FIGS. 4A and 4B by providing a sliding window non-linear convolution instruction, where a subset of the functional units are processed for each of multiple iterations. For example, one row, column or diagonal (four functional units) of the Generalized Memory Polynomial (GMP) matrix of FIGS. 4A and 4B can be processed in each of four iterations. While it takes multiple iterations to process the complete GMP matrix 400, 450, each cycle computes  $N$  outputs with a reduced number of memory accesses, relative to the embodiments of FIGS. 4A and 4B. The coefficients for the  $nxm$  functional units that are active in a given iteration are loaded from one or more look-up tables (LUTs).

FIG. 5 illustrates an exemplary non-linear convolution function 500 that incorporates features of the present invention. The exemplary non-linear convolution function 500 implements equation (1). Generally, the exemplary non-linear convolution function 500 computes the non-linear convolution of input data samples 510.  $M+N-1$  input data samples 510 are needed to produce  $N$  output samples 520  $N$  at a time by the vector processor 200. The exemplary non-linear convolution function 500 processes the input samples in chunks

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505 corresponding to the memory depth  $M$  of the digital pre-distorter (DPD) or other non-linear system.

The non-linear convolution function 500 typically receives the input data samples 510 and processes time shifted versions of the input data samples 510, the "magnitude squared" versions 515 of the input data samples 510 and coefficients. For each time shifted-version (each time lag) along axis 530, the exemplary non-linear convolution function 500 produces an output value 520 in accordance with equation (1).

In the exemplary embodiment of FIG. 5, the input vector 510 comprises  $N_1+N_2-1$  samples of real or complex data (e.g., 32-bit real and 32-bit imaginary) and there  $N_2$  time shifted versions 220 having  $N_1$  samples (16-bit real and 16-bit imaginary) that get convoluted with the coefficients. The coefficients can each be binary values (e.g., or 2 bit, 4 bit, etc).

It is noted that FIG. 5 illustrates the case where  $L=M$ . In the general case where  $L$  and  $M$  are different,  $M+N-1$  samples of  $x$ , and  $L+N-1$  samples of  $|x|^2$  are needed. It is noted that  $L$  indicates the number of rows in the arrays of FIGS. 4 and 5 and  $M$  indicates the number of columns in the array.

FIG. 6 is a graphical illustration of an exemplary functional block diagram 600 that computes the diagonal terms of equation (3) associated with line 442 of FIG. 4A using matrix operations ( $nxm$  functional units at once). Thus, the exemplary functional block diagram 600 comprises functional units associated with the diagonal line 442 of FIG. 4A. The exemplary embodiment processes diagonal, lower diagonal and upper diagonal terms. It is noted, however, that in practice the matrix may be sparse and the non-linear polynomials that are grouped do not have to follow a diagonal, row or column pattern but may be comprised of any group from the larger set of polynomials.

The exemplary embodiment of FIG. 6 recognizes that the GMP matrix is a sparse matrix where the non-zero terms are near the diagonal. In further exemplary variations, the selected sub-set of functional units that are processed in a given iteration can be associated with a given row or column. The exemplary functional block diagram 600 corresponds to one diagonal slice of the sliding window non-linear convolution function out of a total three diagonal, upper diagonal and lower diagonal slices.

The exemplary circuit 600 comprises a plurality of delay elements (not shown) to generate the  $x(n-m)$  terms of equation (3) and delay elements (not shown) to generate the  $|x(n-l)|$  term of equation (4). In addition, the exemplary functional block diagram 600 comprises a plurality of functional units  $f_1()$  through  $f_4()$  620-1 through 620-4 that receive the appropriate  $|x(n-l)|$  term and implement equation (4). The exemplary functional block diagram 600 also comprises exemplary circuitry 625 comprising a multiplier and an adder. The multipliers (x) in each circuit 625 receives the appropriate  $x(n-m)$  term and multiply it with the output of the corresponding functional unit  $f_1()$  through  $f_4()$  620-1 through 620-4. The outputs of the multiplication in each row are added by the adder in the circuit 625 and the outputs of each adder in a given row are summed to generate the diagonal terms of the output  $y(n)$ .

Aspects of the present invention thus recognize that the time shifted versions of input samples can be stored and re-used multiple times in a single cycle, rather than reloading the input values from memory multiple times. For example, as shown in FIG. 6, the time-shifted sample  $x(n-3)$  is applied to four different multipliers and can be re-used four times.

In the exemplary embodiment of FIG. 6, there are  $M=4$  different look-up tables (columns) and  $N=4$  different outputs (rows) per clock cycle. As shown in FIG. 6, each successive

iteration is time-shifted by one. Thus, the second row, for example, computes the second output.

FIG. 7 is a graphical illustration of an exemplary functional block diagram **700** that computes the lower diagonal terms of equation (3) associated with diagonal line **442** (FIG. 4A) using matrix operations ( $n \times m$  functional units at once). The lower diagonal terms are shifted down by one relative to the diagonal line **442** (FIG. 4A).

Generally, the exemplary functional block diagram **700** of FIG. 7 receives the same inputs as the exemplary functional block diagram **600** of FIG. 6, time shifted by one. Thus, the exemplary circuit **700** comprises a plurality of delay elements (not shown) to generate the  $x(n-m)$  terms of equation (3) and delay elements (not shown) to generate the  $|x(n-l)|$  term of equation (4). In addition, the exemplary functional block diagram **700** comprises a plurality of functional units  $f_1()$  through  $f_4()$  **720-1** through **720-4** that receive the appropriate  $|x(n-l)|$  term and implement equation (4). The exemplary functional block diagram **700** also comprises exemplary circuitry **725** comprising a multiplier and an adder. The multipliers ( $x$ ) in each circuit **725** receives the appropriate  $x(n-m)$  term and multiply it with the output of the corresponding functional unit  $f_1()$  through  $f_4()$  **720-1** through **720-4**. The outputs of the multiplication in each row are added by the adder in the circuit **725** and the outputs of each adder in a given row are summed to generate the lower diagonal terms of the output  $y(n)$ .

FIG. 8 is a graphical illustration of an exemplary functional block diagram **800** that computes the upper diagonal terms of equation (3) associated with diagonal line **442** (FIG. 4A) using matrix operations ( $n \times m$  functional units at once). The upper diagonal terms are shifted up by one relative to the diagonal line **442** (FIG. 4A).

Generally, the exemplary functional block diagram **800** of FIG. 8 receives the same inputs as the exemplary functional block diagram **600** of FIG. 6, time shifted by two. Thus, the exemplary circuit **800** comprises a plurality of delay elements (not shown) to generate the  $x(n-m)$  terms of equation (3) and delay elements (not shown) to generate the  $|x(n-l)|$  term of equation (4). In addition, the exemplary functional block diagram **800** comprises a plurality of functional units  $f_1()$  through  $f_4()$  **820-1** through **820-4** that receive the appropriate  $|x(n-l)|$  term and implement equation (4). The exemplary functional block diagram **800** also comprises exemplary circuitry **825** comprising a multiplier and an adder. The multipliers ( $x$ ) in each circuit **825** receives the appropriate  $x(n-m)$  term and multiply it with the output of the corresponding functional unit  $f_1()$  through  $f_4()$  **820-1** through **820-4**. The outputs of the multiplication in each row are added by the adder in the circuit **825** and the outputs of each adder in a given row are summed to generate the upper diagonal terms of the output  $y(n)$ .

The outputs of the exemplary functional block diagrams **600**, **700**, **800** of FIGS. 6-8 are accumulated to generate the final output  $y(n)$ .

FIG. 9 is a graphical illustration of an exemplary functional block diagram **900** that computes the diagonal, upper diagonal and lower diagonal terms of equation (3) in a single instruction call. The exemplary circuit **900** comprises a plurality of delay elements (not shown) to generate the  $x(n-m)$  terms of equation (3) and delay elements (not shown) to generate the  $|x(n-l)|$  term of equation (4). In addition, the exemplary functional block diagram **900** comprises a plurality of integrated diagonal functional units **1000**, as discussed further below in conjunction with FIG. 10, that each generate one output,  $y$ , in a single cycle.

For an exemplary  $4 \times 4$  matrix that processes diagonal, upper diagonal and lower diagonal terms, there are  $3 \times M \times N$  LUTs,  $M \times N$  adders and  $M \times N$  MACs. There are  $3 \times N$  table inputs (e.g.,  $M=8 \rightarrow 24$  different tables).

FIG. 10 is a graphical illustration of an exemplary integrated diagonal functional unit **1000** of FIG. 9 in further detail. As shown in FIG. 10, the exemplary integrated diagonal functional unit **1000** comprises a plurality of delay elements (not shown) to generate the  $x(n-m)$  terms of equation (3) and delay elements (not shown) to generate the  $|x(n-l)|$  term of equation (4). The exemplary integrated diagonal functional unit **1000** generates one output,  $y$ , in a single cycle.

The functional units in a given row of the integrated diagonal functional unit **1000**, such as the three functional units **1010** in the first row, correspond to the diagonal, upper diagonal and lower diagonal terms. The functional units in a given row of the integrated diagonal functional unit **1000**, such as the three functional units **1010** in the first row, receive the appropriate  $|x(n-l)|$  term and implement equation (4).

In addition, the output of each functional unit in a given row of the integrated diagonal functional unit **1000**, such as the output of the three functional units **1010** in the first row, are summed by a first adder **1020**. The summed output of adder **1020** is applied to a multiplier **1030**. The multiplier **1030** receives the appropriate  $x(n-m)$  term and multiplies it with the summed output of the adder **1020**. The outputs of the multiplication in each row are added by an adder **1050** that generates the output  $y(n)$ . The output  $y(n)$  comprises one slice of the sliding window non-linear convolution function (out of four slices).

An exemplary implementation employing  $M=8$  columns by  $N=8$  rows of functional units provides a symmetrical structure. An alternate embodiment of the invention recognizes that an asymmetrical structure may optimize memory bandwidth in certain situations. FIG. 11 illustrates an alternate asymmetric embodiment of the invention, where the exemplary input **1110** comprising a  $2 \times 4$  matrix is processed by an asymmetric  $4 \times 16$  array **1130** of functional units, and the output **1120** comprises a 4 element vector, using a plurality of overlapping windows **1150**. In further implementations, it may be beneficial to have the asymmetry with  $N$  greater than  $M$ , depending on the use case.

The embodiments employing asymmetrical structures recognize that an  $8 \times 8$  convolution may not be optimized for a 16-way single instruction, multiple data (SIMD) operation. Thus, the exemplary embodiment of FIG. 11 employs a 4-way SIMD type of architecture to reduce base processor complexity.

## CONCLUSION

While exemplary embodiments of the present invention have been described with respect to digital logic blocks and memory tables within a digital processor, as would be apparent to one skilled in the art, various functions may be implemented in the digital domain as processing steps in a software program, in hardware by circuit elements or state machines, or in combination of both software and hardware. Such software may be employed in, for example, a digital signal processor, application specific integrated circuit or micro-controller. Such hardware and software may be embodied within circuits implemented within an integrated circuit.

Thus, the functions of the present invention can be embodied in the form of methods and apparatuses for practicing those methods. One or more aspects of the present invention can be embodied in the form of program code, for example, whether stored in a storage medium, loaded into and/or

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executed by a machine, wherein, when the program code is loaded into and executed by a machine, such as a processor, the machine becomes an apparatus for practicing the invention. When implemented on a general-purpose processor, the program code segments combine with the processor to provide a device that operates analogously to specific logic circuits. The invention can also be implemented in one or more of an integrated circuit, a digital processor, a microprocessor, and a micro-controller.

It is to be understood that the embodiments and variations shown and described herein are merely illustrative of the principles of this invention and that various modifications may be implemented by those skilled in the art without departing from the scope and spirit of the invention.

We claim:

1. A method performed by a processor, comprising: obtaining at least one software instruction that performs at least one non-linear convolution function for a plurality of input delayed signal samples; in response to said at least one software instruction for said at least one non-linear convolution function, performing the following steps: generating a weighted sum of two or more of said input delayed signal samples, wherein said weighted sum comprises a plurality of variable coefficients defined as a sum of one or more non-linear functions of a magnitude of said input delayed signal samples; and repeating said generating step for at least one time-shifted version of said input delayed signal samples to compute a plurality of consecutive outputs, wherein said at least one software instruction for said at least one non-linear convolution function is part of an instruction set of said processor.
2. The method of claim 1, wherein said processor comprises a vector processor.
3. The method of claim 1, wherein said plurality of variable coefficients defined by a non-linear function of a magnitude of said input delayed signal samples are implemented using one or more look-up tables.
4. The method of claim 1, wherein said non-linear convolution function models a non-linear system with memory.
5. The method of claim 4, wherein said non-linear system with memory comprises one or more of a power amplifier model and a digital pre-distortion function.
6. The method of claim 1, wherein said at least one non-linear convolution function is implemented using one or more look-up tables having linear interpolation.
7. The method of claim 1, wherein said at least one non-linear convolution function is implemented using one or more look-up tables having polynomial interpolation.
8. The method of claim 1, further comprising the step of loading at least one user-specified parameter from memory into at least one register file.
9. The method of claim 8, wherein said user-specified parameter comprises a look-up table storing values of said non-linear convolution function for one or more input values.
10. The method of claim 1, further comprising the step of reading said plurality of input delayed signal samples directly from memory into functional units for said non-linear convolution function.
11. A processor configured to implement a signal processing function in software, comprising: a memory; and at least one hardware device, coupled to the memory, operative to:

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obtain at least one software instruction that performs at least one non-linear convolution function for a plurality of input delayed signal samples;

in response to said at least one software instruction for said at least one non-linear convolution function:

generate a weighted sum of two or more of said input delayed signal samples, wherein said weighted sum comprises a plurality of variable coefficients defined as a sum of one or more non-linear functions of a magnitude of said input delayed signal samples; and

repeat said generating step for at least one time-shifted version of said input delayed signal samples to compute a plurality of consecutive outputs, wherein said at least one software instruction for said at least one non-linear convolution function is part of an instruction set of said processor.

12. The processor of claim 11, wherein said processor comprises a vector processor.

13. The processor of claim 11, wherein said plurality of variable coefficients defined by a non-linear function of a magnitude of said input delayed signal samples are implemented using one or more look-up tables.

14. The processor of claim 11, wherein said non-linear convolution function models a non-linear system with memory.

15. The processor of claim 14, wherein said non-linear system with memory comprises one or more of a power amplifier model and a digital pre-distortion function.

16. The processor of claim 11, wherein said at least one non-linear convolution function is implemented using one or more look-up tables having linear interpolation.

17. The processor of claim 11, wherein said at least one non-linear convolution function is implemented using one or more look-up tables having polynomial interpolation.

18. The processor of claim 11, further comprising the step of loading at least one user-specified parameter from memory into at least one register file.

19. The processor of claim 18, wherein said user-specified parameter comprises a look-up table storing values of said non-linear convolution function for one or more input values.

20. The processor of claim 11, further comprising the step of reading said plurality of input delayed signal samples directly from memory into functional units for said non-linear convolution function.

21. An article of manufacture, comprising a non-transitory machine readable recordable medium containing one or more programs which when executed by a processor implement the steps of:

obtaining at least one software instruction that performs at least one non-linear convolution function for a plurality of input delayed signal samples;

in response to said at least one software instruction for said at least one non-linear convolution function, performing the following steps:

generating a weighted sum of two or more of said input delayed signal samples, wherein said weighted sum comprises a plurality of variable coefficients defined as a sum of one or more non-linear functions of a magnitude of said input delayed signal samples; and

repeating said generating step for at least one time-shifted version of said input delayed signal samples to compute a plurality of consecutive outputs, wherein said at least one software instruction for said at least one non-linear convolution function is part of an instruction set of said processor.

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